THE GALACTIC DISTRIBUTION (IN RADIUS AND Z) OF INTERSTELLAR MOLECULAR HYDROGEN*

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ABSTRACT

New observations of the galactic longitude and latitude distributions of $\lambda = 2.6$ mm CO emission are presented. Analysis of these spectral-line data yields the large-scale distribution of molecular clouds in the galactic disk and their z-distribution out of the disk. Strong maxima in the number of molecular clouds occur in the galactic nucleus and at galactic radii 4 to 8 kpc. The peak at 4 to 8 kpc correlates well with a region of enhanced 100-MeV γ-ray emissivity. This correlation strongly supports the conclusion of Stecker et al. (1975) that the γ-rays are produced as a result of cosmic-ray interactions in molecular H_2 clouds rather than in HI. One important implication of this is that the interstellar magnetic-field lines to which cosmic rays are confined must therefore not be exluded from these dense clouds.

The width of the cloud layer perpendicular to the galactic plane between half-density points is 105 ± 15 pc near the 5.5-kpc peak. The total mass of molecular gas in the interior of the galaxy exceeds that of atomic hydrogen and is $3 \cdot 10^9$ $M_\odot$ based on these observations.

INTRODUCTION

Until just the last year, there was little appreciation of the possibility that clouds of molecular H_2 rather than atomic hydrogen might constitute the dominant contribution to the

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interstellar mass. The importance of the H_2 gas on a galactic scale was overlooked, essentially because it was impossible to detect from the ground. The rotational and vibrational transitions of H_2 are weak infrared quadruple lines, and observations of the ultraviolet resonance lines are limited to clouds of low visual extinction (< 1 mag) in front of nearby O and B stars (e.g., Spitzer et al., 1973). Our knowledge of H_2 in selected more opaque and more distant gas clouds has instead been deduced from observations of relatively rare trace molecules like CO, CS, and HCN which have fundamental rotation lines at $\lambda = 1 \rightarrow 6$ mm.

Recently, observations of the CO $J = 1 \rightarrow O$ line at 2.6 mm have been extended to surveys of this emission throughout the galactic plane (Scoville and Solomon 1975; and Burton et al., 1975). Scoville and Solomon (1975) used their CO observations to deduce the overall distribution and mass of molecular hydrogen in the galaxy. The relevance of these studies to observations of galactic γ-rays (Fichtel et al., 1975) rests on our early conclusion that "within the region of the galaxy interior to the solar circle, molecular hydrogen, not HI, is the dominant constituent of the interstellar medium." Stecker et al. (1975) have pointed out that the distribution of molecular hydrogen derived from the CO observations is very similar to the "missing" interstellar matter distribution required to account for the observed rise in γ-ray emission at galactic radii 4 to 8 kpc. The consistent conclusion of both analyses is that, at the peak in the molecular cloud distribution ($\bar{\omega} = 5.5$ kpc), perhaps 90 percent of the interstellar gas is H_2, and, as one moves outward in the galaxy, the ratio H_2/HI decreases until, at the solar circle, the two abundances are about equal.

In the following, we first review CO data obtained in the galactic plane ($b = 0$) from which one derives the radial distribution of CO (and H_2) outside the galactic nucleus. Then, some of our most recent observations pertaining to the z-distribution of molecular clouds are discussed. Because the CO emission from the galactic center shows quite different characteristics from that seen elsewhere in the galactic plane, we have devoted a separate section to analysis of the emission seen at $\ell \leq 3°$. Finally, in the last section, we are then able to estimate the mass and surface density contained in interstellar molecular hydrogen by integrating the radial distribution function over galactic radius and z.

CONSIDERATIONS FOR INTERPRETATION OF CO OBSERVATIONS

It is in no way obvious that the CO intensities we have observed at different positions in the galaxy should be a proportional indicator of gas column densities. Very generally, the line is found to be optically thick, and, in clouds having high gas density, the intensities will correlate with gas temperatures, not with gas densities. On the basis of ^{12}CO data alone, it is impossible to tell in what fraction of the clouds observed in the plane the CO is thermalized. Our limited ^{13}CO data obtained at three positions indicates that the CO is probably not thermalized in roughly one-half of the clouds.

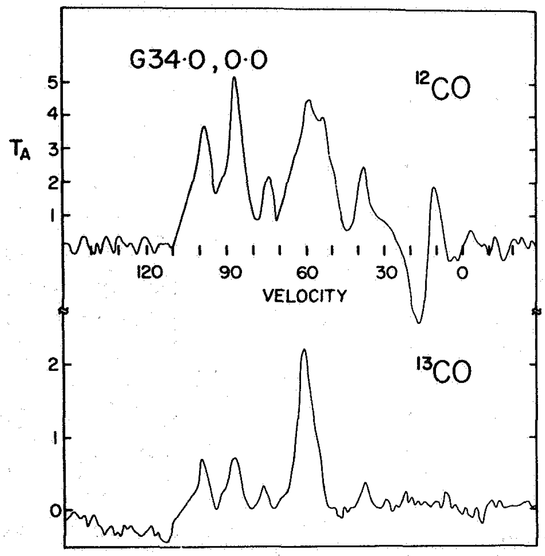

Figure 1. CO and ^{13}CO spectra are shown for the direction $\ell = 34°$, $b = 0°$. Note that there are at least five discrete features in the CO spectra, each of which has a counterpart in ^{13}CO. The negative dip at v = 20 km/s in the CO spectra is caused by the presence of CO emission at that velocity in the reference position 3° above the galactic plane. The intensity units are Rayleigh-Jeans antenna temperatures, K.

Figure 1 shows emission of $^{12}C^{16}O$ and the rarer isotope, $^{13}C^{16}O$, obtained at the position $\ell = 34°$, $b = 0°$. The closest approach of this line of sight to the galactic center occurs at galactic radius 5.5 kpc near the molecular cloud maximum. The discrepancy between the observed intensity ratios $^{13}CO/^{12}CO$ (ranging from 1/2 to 1/6 among the five features seen in figure 1) and the much lower value of the interstellar abundance ratio $[^{13}CO/^{12}CO] = 1/40$ (Wannier et al., 1976) imply that these ^{12}CO lines are optically thick with $\tau > 6$. It must be an important consideration that the CO lines are optically thick, and the observed brightness temperatures are therefore equal to the excitation temperature characterizing the relative J = 1 and J = 0 level populations.

This excitation temperature is determined by the rate of collisions of H_2 with CO, by spontaneous radiative decay ($A_{10} = 6 \cdot 10^{-8}$ sec^{-1}), and by stimulated radiative absorption and emission. In the event that a cloud has $n_{H_2} < 3000$ cm^{-3}, the collisions by themselves would not be sufficient to thermalize the CO levels. However, if in this same region, the CO lines are optically thick, a line photon will be absorbed and scattered approximately τ times before it escapes the cloud. Thus, one may visualize that, when this "radiation trapping" occurs, each collisional excitation is replicated approximately τ times, and the observed excitation temperature will be in some manner proportional to τ. In a more technical treatment of the excitation which solves the full equations of statistical equilibrium for CO (Scoville and Solomon, 1974), we have found that, for a large regime giving subthermal excitation of optically thick CO,

$$T_B \simeq T_{\text{excitation}} \propto (n_{H_2} \cdot n_{CO})^{0.4} \tag{1}$$

Therefore, if the abundance ratio, n_{CO}/n_{H_2} from cloud to cloud is constant,

$$T_B \propto n_{H_2}{}^{0.8} \qquad (2)$$

As the densities increase and $T_{excitation} = T_K$, then T_B gradually loses its dependence on n_{H_2} altogether and develops a linear dependence on T_K.

In most of the clouds outside the galactic nucleus (see "Galactic Center" section), we feel that the densities are insufficient for complete thermalization, and, therefore, an intuition which associates increased CO intensity with increased gas density seems reasonable although it is hardly proven.

RADIAL DISTRIBUTION OF MOLECULAR GAS

The entire run of data from our earlier observations in the galactic plane (ℓ = -10 to +90° sampled once every degree with a 1-arcmin beam) can be displayed in a single longitude-velocity diagram (figure 2). In this representation, a single spectrum observation constitutes a horizontal line of shading. One sees both intense high-velocity emission arising from molecular clouds in the galactic center ($\omega \leqslant 300$ pc; see Scoville et al., 1974) and many individual less-intense features which were sampled in the galactic plane outside the center.

A more useful representation of the CO emission for comparison with γ-ray observations is obtained by using the Schmidt (1965) rotation law to transform from the ℓ, v coordinates of figure 2 to galactic radius (figure 3). This figure provides our best indication of the molecular gas distribution in the galactic plane outside ω = 3 kpc. The vertical scale of figure 3 may be approximately transformed from $\langle T_A \rangle$ to n_{H_2} by setting $n_{H_2} = 4\ \mathrm{cm}^{-3}$ at the 5.5-kpc peak (Scoville and Solomon, 1975). This H_2 distribution matches well that of other population I components except for atomic hydrogen (figure 4). It is very similar to the distribution of discrete HII regions (Mezger, 1970), diffuse ionized gas (Westerhout, 1958; and Lockman, 1976), and is consistent with the pulsar distribution (Seiradakis, this symposium; and Taylor and Hulse, 1976). And, most important for the discussion at hand, the H_2 distribution is identical to the γ-ray emissivity (Stecker et al., 1975) within observational errors and the uncertainty involved in unfolding the γ-ray longitude distribution. All of these results have been confirmed by the finer spaced, higher sensitivity CO observations of Gordon and Burton (1976) at b = 0 and our most recent, higher sensitivity observations in 1 and b (Solomon et al., 1976).

THICKNESS OF THE MOLECULAR GAS DISK

When making a comparison with γ-ray data, a major shortcoming of the published CO observations is that the 1-arcmin CO beam observed only the galactic plane, whereas the γ-ray data have a much lower angular resolution, including contributions from over 5° of latitude. Our newest observations and those of Cohen (1976) are therefore especially addressed to estimating the thickness of the molecular cloud layer. We have observed along strips perpendicular to the galactic plane from b = -1 to +1° every even degree of longitude in the

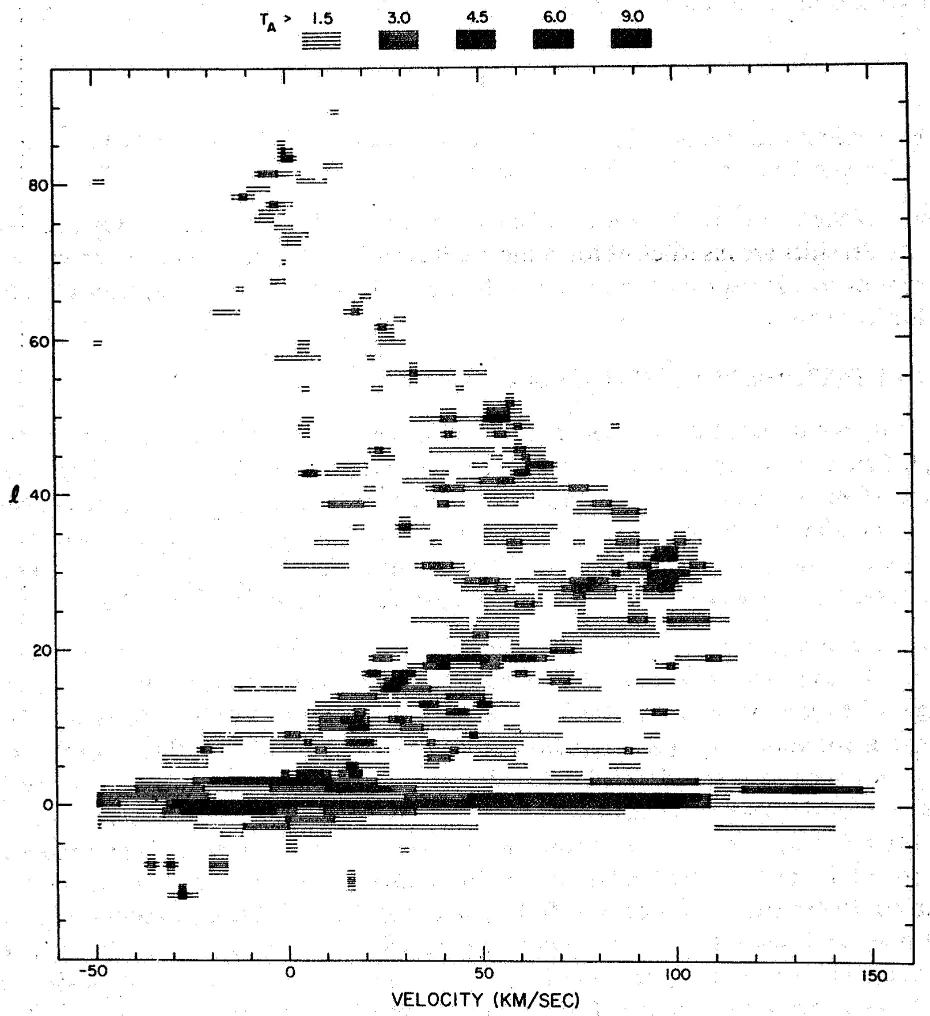

Figure 2. The intensity of CO emission along the galactic equator is shown as a function of longitude and velocity. Molecular emission tends toward lower longitudes and more positive radial velocities as compared with 21 cm (see Kerr, 1969), indicating that the molecules are concentrated toward the center of the galaxy. A version of this figure, spanning more velocities (± 300 km s^{-1}) and therefore containing the full range found in the galactic center, may be found in Scoville (1975).

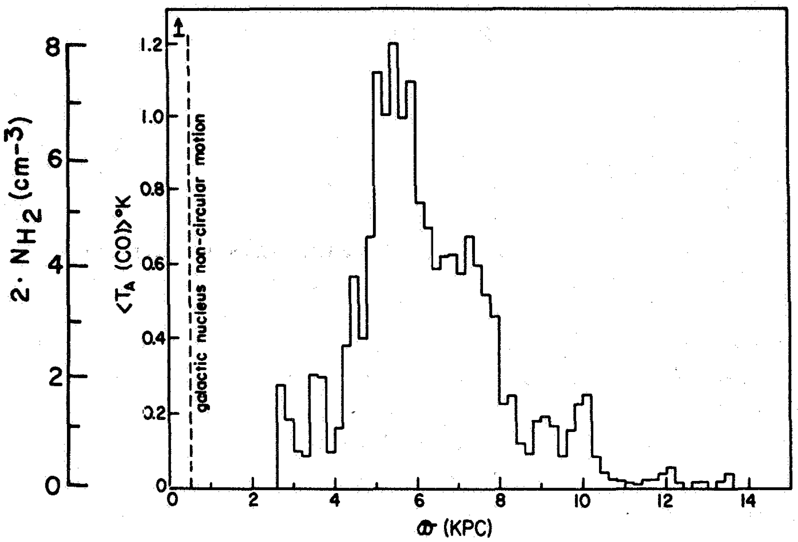

Figure 3. The mean CO antenna temperature as a function of radius in the galaxy ω, was calculated using the Schmidt (1965) rotation law to transform ℓ, v in figure 2 to ω. We use only data at $\ell \geqslant 10°$ in order to exclude the galactic center where much of the gas clearly is not in pure rotation. Note the sharp peak in CO at a radius of 5.5 kpc and the dramatic falloff toward the Sun and beyond. The vertical scale may also be converted to H_2 surface density through a normalization to 25 $M_\odot$ pc^{-2} at the 5.5-kpc peak. (See the last section of this paper.)

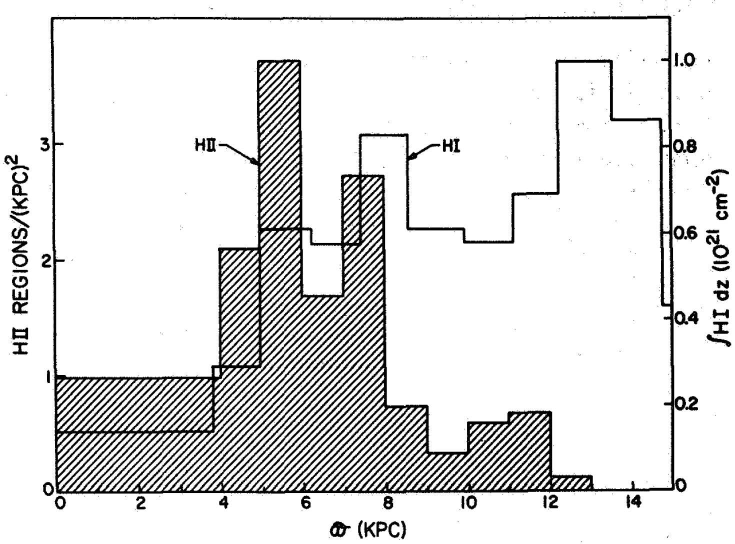

Figure 4. The surface density in giant HII regions (shaded area; Mezger, 1970) and free-free continuum radiation (figure 16 in Westerhout, 1958) show a remarkable similarity to the radial distribution of CO (figure 3). In contrast, the HI surface density varies little with galactic radius (Van Woerden, 1965).

range $\ell = 0$ to $50°$. Although we have yet to fully analyze these new observations, samples in the form of integrated line intensities are shown in figures 5 and 6 and are tabulated in table 1.

Interpreting the intensity integral as a proportional indicator of the molecular column densities, we may use these data for estimating both the thickness and the central latitude of the clouds. The full width in latitude to half-intensity varies from $0.^\circ7$ to $1.^\circ0$ (excluding $\ell = 0°$). The mean latitude of this emission significantly deviates from the galactic plane in the 20 to 40° longitude range where $\langle b \rangle \simeq -0.^\circ2$, and most of the emission integral is contributed by gas in the 4- to 8-kpc ring. This amounts to a displacement $\langle Z \rangle$ of 40 pc below the plane. From the latitude thickness of the emission observed near the terminal velocity* at many longitudes $\ell = 10$ to $50°$, we have estimated that half-density points on either side of the plane are separated by 105 ± 15 pc at radii $4 \rightarrow 8$ kpc. This is in agreement with the crude value of 130 pc found in our earlier survey (Scoville and Solomon, 1975) and the estimate of 118 pc found by Burton and Gordon (1976) from data at $\ell = 21°$. A more sophisticated analysis of the data at all longitudes is planned in order to search for systematic variations of the scale height with galactic radius (Solomon et al., 1976).

Perhaps a most relevant quantity against which one should compare the γ-ray observations is the double integral of the line intensity over all velocities and over galactic latitude (last column of table 1). That the longitude dependence of this double integral is similar to the longitude distribution of 100-MeV γ-ray emission argues most persuasively in favor of the γ-rays being produced within molecular clouds. Indeed, this is perhaps the most straightforward comparison one can make. The alternative of comparing the radial distributions of γ-ray and CO emissivities which we have used in the past requires an assumption of azimuthal symmetry about the galactic origin. For a mere comparison of the two observations, the unfolding of both sets of data (in different ways) does not gain anything.

THE GALACTIC CENTER

One enigma in the comparison of CO and γ-ray emissions still remains. Within the inner 3° of longitude about $\ell = 0°$, there is a system of very dense, massive clouds. Here, the integrated CO emission is therefore 2 to 3 times the value at $\ell = 10$ to $30°$ (figures 5 and 7), yet the γ-ray emission varies less than 50 percent over the same longitudes. In interpreting the CO emission elsewhere in the galactic plane, it was convenient to imagine that all clouds had a similar kinetic temperature which was slightly above the observed brightness temperatures. One could justify this assumption observationally on the basis that all lines observed were weak (most had $T_A < 4$ K). However, in the galactic center clouds, the assumption is clearly not valid inasmuch as several of the CO features have $T_A \gtrsim 20$ K. In this region, there are also several infrared sources (e.g., Hoffman et al., 1971) of sufficiently high luminosity to

*Emission at the highest positive velocity in each line-of-sight with $\ell < 90°$ is produced at the point of closest approach to the galactic center. Therefore, the distance to gas-producing emission at these "terminal" velocities is unambiguous.

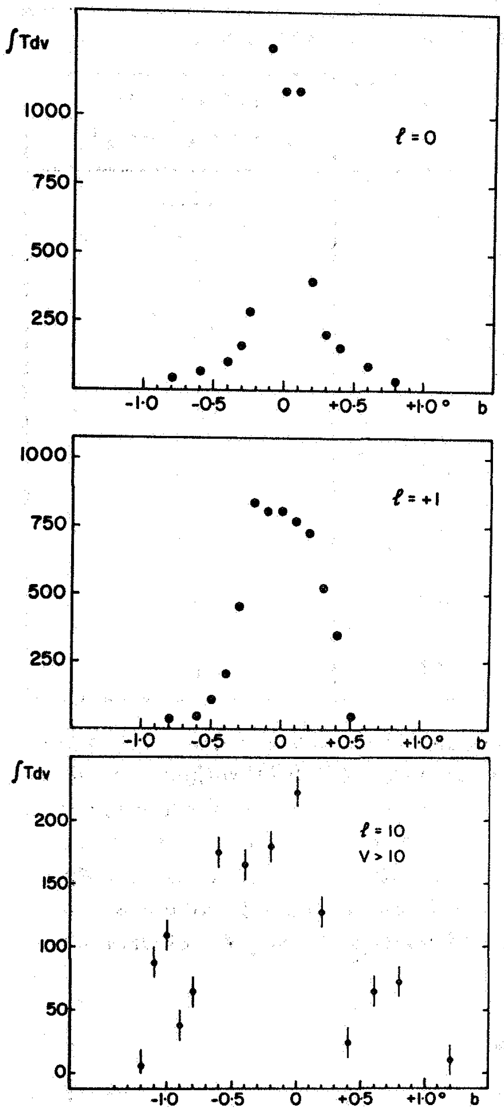

Figure 5. The distribution of integrated CO intensity $\int T_A\, dV$ in K·Km s^{-1} is shown perpendicular to the galactic plane at ℓ = 0, 1, and 10°.

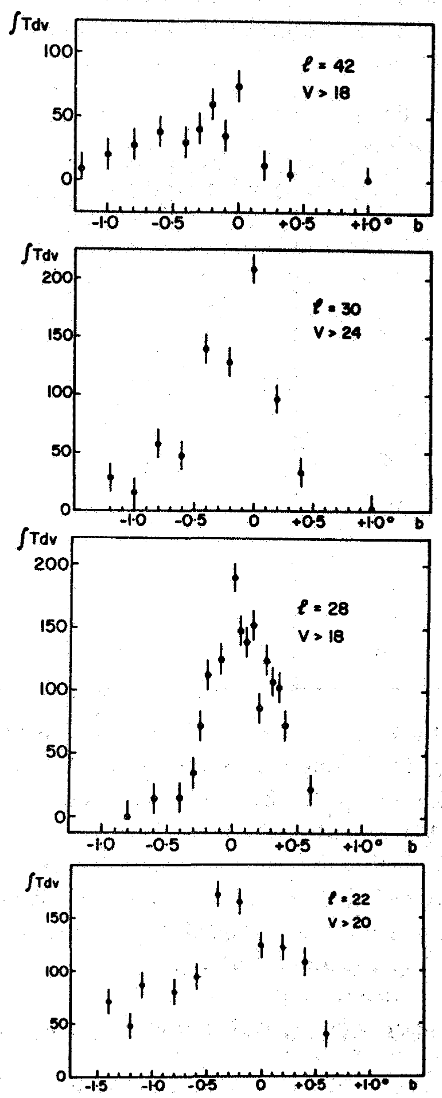

Figure 6. The distribution of integrated CO intensity $\int T_A\, dV$ in K·Km s^{-1} is shown perpendicular to the galactic plane at ℓ = 22, 28, 30, and 42°.

Table 1
Sample Data on the Latitude Distribution of CO Emission

ℓ (°)	$\int T_A\, dV$ at b = 0° (K·km s^{-1})	<b> (°)	$\int db \int T_A\, dV$ (10^{3} ° · K · km s^{-1})
0	1200	0	29
1	775	0	31
10	200	-0.2	15
22	170	-0.3	13
30	200	-0.1	7.4
36	110	-0.2	4.4
42	70	-0.3	3
50	37	-0.1	1

heat the dust and gas to $\gtrsim 30$ K. And, if the CO transition is close to thermalization, a change in T_K can bring about an equal change in the observed T_A (CO) without any change required in n_{H_2}. (See the second section of this paper, "Considerations for Interpretation of CO Observations.") We therefore judge that the increase in CO emission going from $\ell > 3°$ to $\ell < 3°$ does not accurately reflect column-density variation, but instead is due largely to kinetic temperature changes. We have previously obtained the total mass, $4 \cdot 10^7$ - $10^8 M_\odot$ of H_2, inside $\ell = 3°$ from analysis of detailed CO and ^{13}CO observations there (Scoville et al., 1974).

MOLECULAR CLOUD DENSITIES AND MASS

An important feature of the molecular hydrogen distribution, as deduced from the CO observations, is the extreme concentration of gas into clouds. The fraction of space filled by clouds is approximately 0.007 near the peak in the 4- to 8-kpc region with a mean molecular hydrogen density within the clouds of 670 cm^{-3}, corresponding to a smoothed-out density of 2 to 5 cm^{-3} (see figure 3 and Scoville and Solomon, 1975). The corresponding number derived by Gordon and Burton (1976) is 2 cm^{-3}.

The relative abundance of CO within clouds is $[CO/H_2] \approx 3 \cdot 10^{-5}$. This abundance ratio must itself depend on the density and opacity of the cloud. Low-density or low-opacity clouds of the type observed by the Copernicus satellite (Jenkins, this symposium) have a much lower $[CO/H_2] \sim 10^{-8}$ and therefore have much weaker CO emission per H_2 molecule. The mass of H_2 in these low-opacity clouds is an additional component to that determined through millimeter wave CO surveys.

Combination of the measured width and density estimate ($4\ H_2\ cm^{-3}$) yields a mass density of $25\ M_\odot\ pc^{-2}$ at 5.5 kpc (figure 3). Integrating this surface density function over the galactic disk, we find a total mass of $3 \cdot 10^9\ M_\odot$ in interstellar H_2 interior to the solar circle.

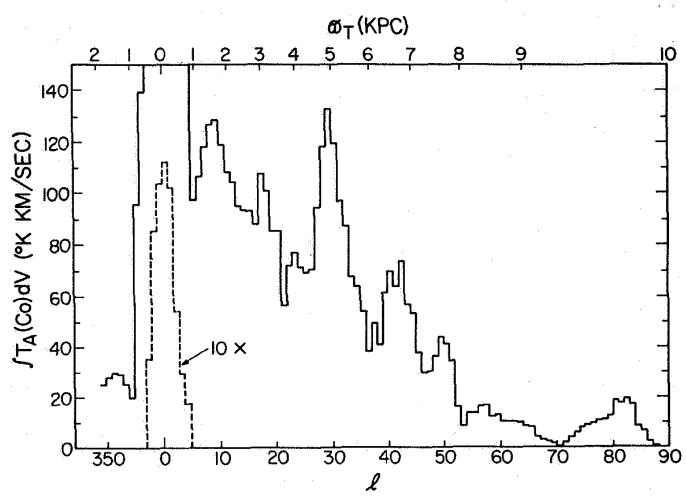

Figure 7. The very strong emission from the galactic center may be appreciated in this graph of integrated intensity as a function of galactic longitude at b = 0.

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